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Search for $H \rightarrow c\bar{c}$ at a Multi-TeV Muon Collider

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A Multi-TeV ($\sqrt{s}$ = 1.5 - 10 TeV) Muon Collider providing $O(ab^{-1})$ integrated luminosity will be a great opportunity to probe the most intimate nature of the Standard Model (SM) and the Electroweak Symmetry Breaking mechanism, allowing the precise measurement of the Higgs couplings to several SM particles. The study of the Higgs boson couplings to the second generations of fermions is of particular interest due to sensitivity to a whole class of new physics models. It is also true that this measurement is extremely challenging, because of the small branching ratio. Indeed, it is currently not accessible at LHC, where the quantum chromodynamics processes are overwhelming. In this paper it is explored, for the first time, the search for $H \rightarrow c\bar{c}$ at a Multi-TeV Muon Collider. The $\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow c\bar{c}\nu\bar{\nu}$ signal process has been fully simulated and reconstructed at $\sqrt{s} = 1.5\ TeV$ with a preliminary detector design, along with the main physics backgrounds. The machine background originated from the decay of beam muons, the so-called Beam Induced Background (BIB), is not included in this preliminary study. A c quark-tagging algorithm has been developed, combining several observables in a single discriminator using Machine Learning techniques, with the goal to improve the rejection of jets coming from b-quark and u-d-s-g hadronization. A first estimate of the precision on the Higgs coupling with c-quark reachable with a Muon Collider machine is presented. The relative uncertainty on the coupling at $\sqrt{s} = 1.5\ TeV$ is estimated to be 5.5 %. A projection to $\sqrt{s} = 3\ TeV$ shows that the precision improves with increasing energy, reaching the value of 2.6%.

This work has been performed within the *Muon Collider Detector Design and Performance group* [1].

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1. Introduction

The highest scientific priorities identified in the update of the European Strategy for Particle Physics [2] are the study of the Higgs boson and the exploration of the high-energy frontier. These are two crucial and complementary ways to address the open questions in Particle Physics.
In this perspective, a future Muon Collider experiment has been proposed as an unconventional machine with several advantages with respect to the traditional hadronic and e^+e^- colliders. Nonetheless this novel approach poses some new technical challenges that are currently object of study, as the mitigation of the BIB. Indeed, the interaction region and the machine-detector interface have been specifically designed to face this issue [3].
The Muon Collider would have a discovery machine potential as well as the opportunity to measure precisely the Higgs couplings to several SM particles and the Higgs self-couplings. In this work, the search for $H \to c\bar{c}$ at the Muon Collider is simulated for the first time and a very preliminary estimate of the precision achievable on the Higgs-to-c-quark coupling is given, for the time being without the BIB overlay. The central feature of this search is the identification of charm quark jets. To fully exploit differences between flavours of jets, a good vertexing capability and jet energy resolution is required. The former is accomplished through a $5\mu m \times 5\mu m$ vertex detector while the latter with the of use of high granularity calorimeters and a novel Particle Flow algorithm for particle reconstruction and identification. Detailed information on detector and reconstruction algorithm can be found respectively in Refs. [4] and [5].

2. Simulated event samples

The signal under study is the Higgs decay into charm quarks, where the Higgs Boson is produced through WW fusion, that is the dominant process for Higgs production at this energy ($\sqrt{s} = 1.5\ TeV$). The considered background consists of processes with two jets in the final state. For what concerns the peaking background in the Higgs mass region, the decays $H \to b\bar{b}$ and $H \to gg$ are considered as their branching ratios are respectively 20 and 3 times higher than the signal one. The non-peaking background is represented by processes with two jets and two leptons of any kind in the final states. Signal and background processes are simulated using Pythia8 [6] and MadGraph5 [7] as event generators. All the samples produced are exhaustively described in Ref. [8]. The Muon Collider detector response simulation and the subsequent reconstruction are performed with ILCSoft [9]. The BIB is not overlaid in this analysis.

3. The c-jet identification

The main feature of jets arising from hadronization of heavy quarks is the presence of secondary vertices (SVs) related to heavy-hadron decay, since the hadrons containing bottom or charm quarks have sizable lifetimes which can be measured inside the detector. The characteristic flight length, measured in terms of the lifetime at rest τ , is cτ = 400 μm - 500 μm for bottom hadrons and cτ = 20 μm - 300 μm for charm hadrons. This leads to typical secondary-to-primary vertex displacements of the order of millimetres or more, depending on the hadron Lorentz factor.
Moreover tracks originated from SVs have large signed (sign of the scalar product between the

impact parameter vector and the jet axis) impact parameters (SIPs) which are more likely to be positive. Lastly, the semi-leptonic decays of heavy hadrons lead to the presence of non-isolated low-energy electrons and muons (collectively called soft leptons) that can be exploited in the tagger, as well. Thus, the variables used for heavy-flavour tagging can be divided into three categories: secondary vertex (examples in Figures 1 and 2), track (example in Figure 3) and soft lepton (example in Figure 4) related variables.

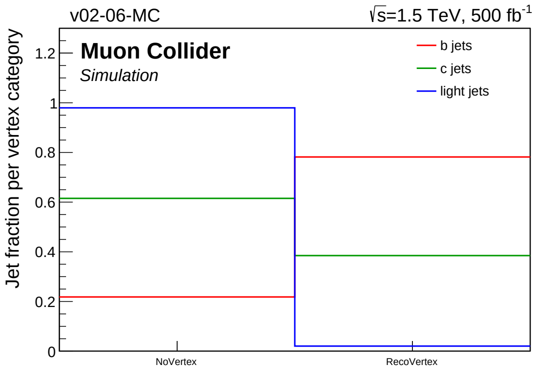

Figure 1: Jet fraction per vertex category. "NoVertex" contains jets with no SV, while "RecoVertex" contains jets with at least a SV in it.

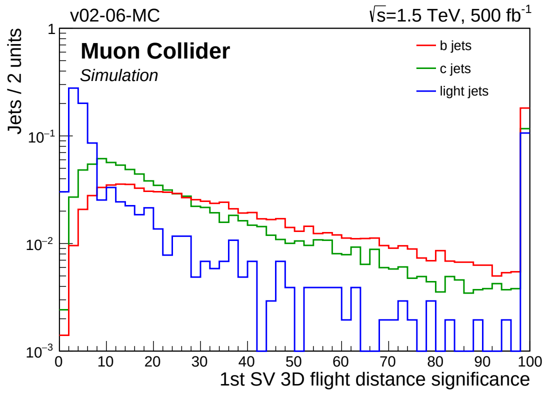

Figure 2: 3D flight distance divided by its uncertainty (significance) for the first SV. SVs are ordered by increasing uncertainty on their 3D flight distance.

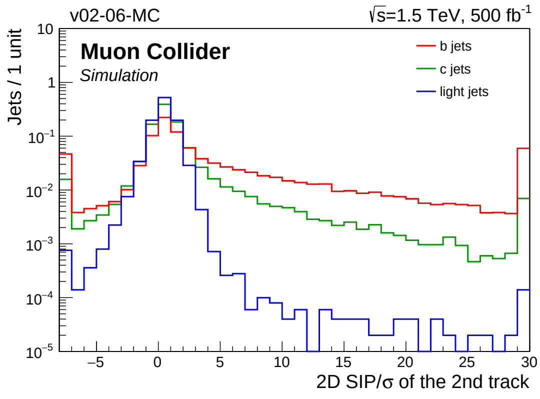

Figure 3: 2D SIP divided by its uncertainty (significance) for the second track. Tracks are ordered by decreasing 2D SIP significance.

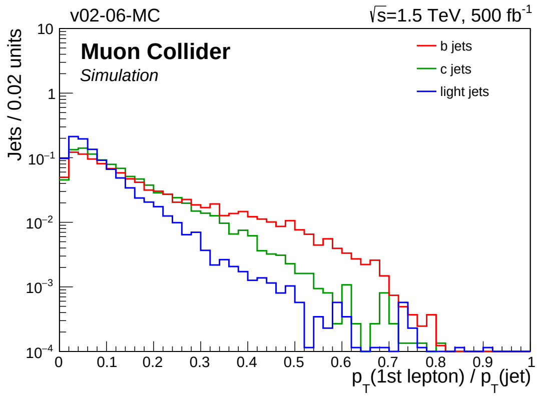

Figure 4: Transverse momentum of the first lepton divided by jet transverse momentum. Leptons are ordered as tracks.

A comprehensive description of the features exploited in the tagger can be found in Ref. [8]. The distributions of the tagging variables for c jets lie in between the distributions for b and light flavour jets. This is due to the lifetime of c hadrons being shorter than the b hadron one, to the lower secondary vertex multiplicity and also to the smaller c quark mass results in a smaller track transverse momentum relative to the jet axis. Therefore, it is particularly challenging to efficiently identify jets originating from c quarks. Several variables are combined in the c tagging algorithm, since no single variable is by itself sufficient to achieve a good discrimination. Two binary classifiers

has been trained: one for discriminating c jets from b jets (*CvsB*) and the other for discriminating c jets against light flavour jets (*CvsL*).
The performances of the classifiers are evaluated and compared to the CMS [10] and CLIC [11] ones in Table 1. CMS is taken as a reference as the implemented algorithm is inspired by the CMS analysis, while CLIC is an example of future lepton collider. CLIC performance is reported without the overlay of the $\gamma\gamma \to hadrons$ background, for a direct comparison with the results of this paper.

	b misid. probability			**light misid. probability**		
c-tag eff.	MuColl (w/o BIB)	CMS	CLIC (w/o overlay)	MuColl (w/o BIB)	CMS	CLIC (w/o overlay)
50%	7.5%	11%	7%	2.3%	14 %	3 %
60%	10%	14%	11%	6.3%	25 %	6 %
70%	14%	20%	15%	16%	40 %	12 %
80%	19%	26%	23%	31%	55 %	25 %
90%	28%	40%	32%	55%	75 %	52 %

Table 1: Beauty and light-flavour contamination for fixed values of c tagging efficiencies at Muon Collider (w/o BIB), CMS and CLIC (w/o overlay).

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4. Event selection and final results

The two trained classifiers CvsB and CvsL are applied in the analysis to reject b jets and light flavour jets. The jets surviving the flavour tagging are used to build the Higgs candidates (detailed information on the chosen working point in Ref. [8]). If more than two jets are available, the two with the highest transverse momentum are taken. Finally, several topological selection are applied in order to suppress the prompt jet background: the separation between jets in the $\eta - \phi$ plane is required to be smaller than 3, the Higgs candidate is required to have energy greater than 130 GeV, transverse momentum greater than 30 GeV, and invariant mass in the range [110, 130] GeV.

The final number of expected signal events (S) and background events (B) are used for computing approximatively the relative uncertainty on the $H \to c\bar{c}$ production cross section and on the Higgs-to-c-quark coupling, following Ref. [12]. Table 2 summarizes the results and shows the projection at $\sqrt{s} = 3\ TeV$, $\mathcal{L} = 1300\ fb^{-1}$, obtained assuming the same fraction of surviving events per each sample and scaling the results to cross section and luminosity at the increased center of mass energy. These estimates are very preliminary but already show the potential of the Muon Collider, if an efficient machine background mitigation strategy is adopted.

$\sqrt{s}$ $[TeV]$	$\mathcal{L}$ $\left[fb^{-1}\right]$	**S**	**B**	$S/\sqrt{S+B}$	$\Delta\sigma/\sigma$	$\Delta g_{Hcc}/g_{Hcc}$
1.5	500	378	1205	9.5	10.5 %	5.5 %
3.0	1300	1565	4337	20.4	4.9 %	2.6 %

Table 2: Signal and background yields, signal significance, relative uncertainty on $H \to c\bar{c}$ production cross section and relative uncertainty on the Hcc coupling at 1.5 and 3 TeV, without BIB overlay.

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